Evapotranspiration Estimates for the Closed Norman, Oklahoma Landfill

Christine Gossard
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Evapotranspiration Estimates for the Closed
Norman, Oklahoma Landfill

By
Christine Michelle Gossard

This thesis for honors recognition has been approved for the Department of Mathematics,
Engineering, Physics and Computer Science, Carroll College, Helena, Montana.

Director

Reader

Reader

April 11, 1998
Abstract

By
Christine Michelle Gossard

An abandoned landfill in Norman, Oklahoma has been designated a National research site for the USGS's toxic substances hydrology program. One aspect of the project is to account for all moisture fluxes at the site. An important component is the modeling of infiltration through the landfill cap as this helps determine the amount of leachate production.

My particular project attempts to account for the amount of evapotranspiration (ET) from the surface, which ultimately reduces the water penetrating the cap. ET information is then used in the larger infiltration model. My work compared several models that are frequently used to estimate ET. I evaluated models from the main subgroups of ET methods: temperature-based - Thomthwaite; radiation-based - Priestley-Taylor, Jensen-Haise; and combination wind and radiation based - Blaney-Criddle, Penman Combination and Penman-Monteith.

The results of each model are compared to actual pan evaporation measurements for May and June to test the accuracy of the models. The findings for these two months indicate a close correlation between the actual measurements and most of the models. After analyzing the results, the Penman-Monteith model is recommended for use in the larger infiltration model. The Penman-Monteith model matches the pan evaporation data as closely as other models and accounts for more of the physics at the site. Because the Penman-Monteith model incorporates the plant activity at the site, it predicts the least water loss through ET during the winter months, which is expected with the thick hatch at the site.
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Finally, I would like to express my gratitude to all the faculty members who provided both an excellent education and unending support throughout my years at Carroll College.
Introduction:

The Norman, Oklahoma landfill was operated as an open dump for approximately 60 years; it was capped and closed in the early 1980's. A portion of the landfill lies below the water table and refuse disposed of before 1960 is in the saturated groundwater zone. The site was capped in three sections with approximately two feet of clay and a layer of topsoil. It was then planted with vegetation (mostly native grasses and brush). Field measurements have detected a leachate plume that emanates from the landfill and extends southward toward the nearby South Canadian River. Because the landfill, and its subsequent contamination problem, is typical of many U.S. landfills operated during the same time period, it was designated as a research site for the United States Geological Survey's toxic substances hydrology program in 1994. Since that time, flow and transport studies have escalated, including the work presented herein.

The purpose of the clay cap is to inhibit water from percolating through to the refuse and producing more leachate. A mathematical model using data collected from the site can estimate how much precipitation is getting into the refuse. The model currently being used is based upon the mixed form of Richard’s equation and is solved by a finite element method. For more information see Celia (1990).

For this infiltration model to predict accurately the flow of water through the cap at the Norman landfill, more detailed information is needed about the surface flux conditions. The surface flux is the combination of infiltration and evapotranspiration where evapotranspiration (ET) is the combination of evaporation from the surface and plant
Infiltration replenishes groundwater by taking moisture into the soil from the surface. This moisture is provided by rainfall. However, evapotranspiration works to deplete the moisture of the soil and contributes to the net boundary flux.

The goal of my research was to quantify the evapotranspiration at the landfill. Various mathematical models were implemented to get an estimate of the ET. A secondary goal was to determine an adequate model for this process that could be incorporated into the larger infiltration model. (It was decided that it would be better to overestimate the ET rate rather than underestimate for the purposes of the larger model.) To determine the accuracy of the models it was necessary to find actual evaporation data to compare with the results. No data were available for the Norman area. Therefore, pan evaporation data from Chickasha were used as a measure of comparison. Chickasha is located about 30 miles southwest of Norman and is the closest site that still takes pan evaporation measurements. (Pan evaporation is measured by recording the depth of the water in the pan each day and taking the difference in depth from one day to the next to be the daily evaporation.)

Other meteorological data were obtained from an Oklahoma Mesonet site at the Norman landfill. The Mesonet is a network of 114 automated measurement stations across Oklahoma that record various meteorological data every five minutes and send these data every fifteen minutes via the Oklahoma Law Enforcement Telecommunications System. These data are received and verified at the Oklahoma Climatological Survey located on the University of Oklahoma campus and can be accessed twenty-four hours a day.
Data from the Oklahoma Mesonet were used in the models to calculate ET over the entire year of 1997. My research is intended to predict ET only in the Norman area, specifically at the abandoned landfill. (My research focussed on the east cell and newer west cell of the landfill.) This is limited somewhat, as some meteorological data were unavailable for Norman. The ratio of actual to possible sunshine hours was obtained from Oklahoma City, which is twenty miles north of Norman. As mentioned above, pan evaporation data came from Chickasha. The temperature conditions at Chickasha were compared to those of Norman in order to expose any great deviations. The models used to estimate potential evapotranspiration (PET) and actual evapotranspiration (ET) were obtained from various sources including journals and texts (Allen 1986; Allen and Pruitt 1986; Brutsaert 1982; Brutsaert and Stricker 1979; Chow 1988; Hatfield and Allen 1996; Hillel 1980; Parsons 1995). I tried to choose models that were not site specific, but rather were based on general physical principles.

This report is intended to show the methods used to model ET at the landfill and to present and compare the results of each model with the other models and, where possible, with actual measurements. The literature review presents the equations used in my study and the input data needed for each model. The methods section outlines the criteria used to evaluate each of the models. The results section includes comparisons of each model with the pan evaporation data and the Penman-Monteith ET model. Finally, the conclusion summarizes the results and suggests future research topics.
Literature Review:

Evapotranspiration can be measured directly or estimated by various models. Some methods of measurement mentioned by Salisbury and Ross are lysimeters and enclosures (1985). Both methods use an accurate mass balance to calculate ET by recording how much moisture is added to the system and how much is infiltrating into the soil. The difference in these two measurements is the evapotranspiration. However, there might be some deviation from actual ET since the measured area is altered by confinement (a pan enclosing a portion of the soil and vegetation for the lysimeter method, and a “tent” enclosing a larger portion of the area for the enclosure method). (See the Glossary for a more detailed description of these devices.) Due to monetary and time constraints, I was unable to take actual ET measurements at the landfill site. Instead, it was necessary to estimate the evapotranspiration with mathematical models.

Most available methods for the calculation of ET do not consider the plant’s resistance to transpiration, but instead estimate the ET based solely upon meteorological input and surface roughness. Because plant resistance is not incorporated into the models, the evapotranspiration calculated is often termed reference or potential evapotranspiration (PET). Despite the connotations of “potential,” this is not the maximum obtainable ET because different crops are capable of transpiring more than this amount during different stages of their growth cycle (Cuenca 1982).

Once a satisfactory PET estimate is calculated, it must be scaled appropriately to estimate actual ET. The PET is developed for a specific crop, usually grass or alfalfa. This
reference must then be scaled by crop coefficients to estimate ET for other crops under
the same conditions, or by a limiting factor, such as soil moisture, to estimate ET for the
reference crop. The United Nations Food and Agricultural Organization (FAO) and
various other organizations list crop coefficients. The FAO has also developed regression
equations to calculate the coefficients needed for some of the ET models. Specifically,
these are the Blaney-Criddle, Penman, and radiation and pan evaporation methods
(Frevert 1983). These or other coefficients are needed to scale properly the PET predicted
by the various methods.

Parsons noted another method of scaling PET in order to obtain an estimate of actual ET
(1995). He mentions a ratio of available soil moisture to maximum available soil
moisture at plant root depth. The resulting percentage is used to scale the PET and
calculate an estimate of ET. This method is useful when considering how the available
moisture at root depth affects the evapotranspiration rate. This is the method I have used
to scale the potential ET in my research.

To calculate ET, meteorological data are necessary for input. These data include
temperature, net or incoming solar radiation, relative humidity, and wind speed. The
Norman landfill is equipped with Mesonet towers that collect and transfer these and other
data directly to the University of Oklahoma campus every five minutes. This allows for
more accurate modeling based upon small time steps. However, for my research I
concentrated on daily estimates of ET and used daily totals and averages of the Mesonet
data. To estimate ET for larger time periods, I summed the daily-calculated values over

5
the appropriate time.

Some idea of regional evapotranspiration can be gained through pan evaporation. However, this method is most indicative of open-water evaporation and must be scaled by crop factors in order to estimate ET. Pan coefficients provided by Frevert were used to scale the data from Chickasha (1983) (Appendix 1).

A more common method of estimating ET entails modeling individual sites using meteorological data and site characteristics. Many different models can be used to estimate evapotranspiration, each based upon different meteorological data. These range from complex combination equations that use temperature, radiation, and wind speed — the Penman Combination (Hatfield and Allen 1996) — to those based on a single variable — the Thornthwaite (Parsons 1995).

Tabulation of equation information:

There are three major types of models used for the estimation of evapotranspiration — those based on radiation, those based on temperature, and those based on a combination of radiation, temperature, and wind with aerodynamics. Models can also be classified depending on whether they predict ET or potential ET. Table 1 shows the models that I used and the category into which each one fits.
Table 1. Summary of category types for models

<table>
<thead>
<tr>
<th>Model / Type</th>
<th>Radiation</th>
<th>Temperature</th>
<th>Combination</th>
<th>PET</th>
<th>ET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blaney-Criddle</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Jensen-Haise</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Thomthwaite</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Priestley-Taylor</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Penman</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Advection-Aridity</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Penman-Monteith</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

Each model requires different units and types of meteorological data to compute the evapotranspiration rate. Table 2 organizes some of the necessary input parameters for each equation.

Table 2. Input parameters and required units for model equations

<table>
<thead>
<tr>
<th>Model/Units</th>
<th>Temp. Type</th>
<th>Radiation Type</th>
<th>R. Humidity</th>
<th>Elevation</th>
<th>2m Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thomthwaite</td>
<td>Avg. daily [°C]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jensen-Haise</td>
<td>Avg. daily [°C]</td>
<td>Avg. incoming [ly/day]</td>
<td>mean [m]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blaney-Criddle</td>
<td>Avg. daily [°C]</td>
<td>Daily min. mean [m]</td>
<td>mean [km/day]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Penman</td>
<td>Avg. daily [°C]</td>
<td>Avg. net [W/m²]</td>
<td>Avg. daily mean [m]</td>
<td>mean [km/day]</td>
<td></td>
</tr>
<tr>
<td>Monteith</td>
<td>Avg. daily [K]</td>
<td>Avg. net [cal/cm² day]</td>
<td>Avg. daily mean [m]</td>
<td>mean [m/s]</td>
<td></td>
</tr>
<tr>
<td>Advection-arith.</td>
<td>Avg. daily [K]</td>
<td>Avg. net [W/m²]</td>
<td>Avg. daily mean [m]</td>
<td>mean [m/s]</td>
<td></td>
</tr>
<tr>
<td>Priestley-Taylor</td>
<td>Avg. daily [°C]</td>
<td>Avg. net [W/m²]</td>
<td></td>
<td></td>
<td></td>
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</table>

Some models also require preliminary calculations for vapor and atmospheric pressures. For all models, vapor pressures (in mb) are calculated from the average daily temperature (in °C) by

\[ e = 6.1805 \cdot \text{Exp}(0.06466 \cdot T). \] (1)

Direct measurements of atmospheric pressure were unavailable; therefore, atmospheric
pressure (in mb) was calculated from the mean elevation (in m) as

\[ p = 1013 - 0.1055 \times ELEV. \]  

(Equations for atmospheric and vapor pressures obtained from Parsons 1995.) These pressures are then converted to the necessary units for use in the ET models. Table 3 summarizes the types of pressure needed for each model and the required units.

**Table 3. Pressure unit requirements for models**

<table>
<thead>
<tr>
<th>Model/Units</th>
<th>Blaney..</th>
<th>Thornthwait</th>
<th>Jensen..</th>
<th>Penman</th>
<th>Priestley..</th>
<th>Monteith</th>
<th>Advection..</th>
</tr>
</thead>
</table>
Potential Evapotranspiration Equations:

The current model being used at the University of Oklahoma to determine the infiltration rate at the landfill requires a PET equation. Thus, although the Penman-Monteith equation has been suggested as a standard for ET calculation, it was necessary to determine an adequate PET model for use in the infiltration model. This section includes five different equations used to calculate PET and a brief description of each. All terms and symbols used in these and the actual ET equations are defined in the Glossary.

**FAO Blaney-Criddle—**

The FAO Blaney-Criddle model, as discussed by Allen and Pruitt (1986), is an empirically derived equation based on temperature, wind speed, relative humidity, and daily hours of sunshine. The equation is of the form

\[
PET = [a + b(P(0.46T + 8.13))]\left[1 + 0.1 \frac{ELEV}{1000}\right]
\]

where

\[a = 0.0043R_{h_{min}} - N_{ratio} - 1.41\]
\[b = 0.81917 - 0.00409227P + 1.0705N_{ratio} + 0.065649U_{day} - 0.00597R_{h_{min}}N_{ratio} - 0.000597R_{h_{min}}U_{day}\]

\[R_{h_{min}} = \text{minimum relative humidity in a 24-hour period}\]
\[N_{ratio} = \text{ratio of actual to possible sunshine hours during the day}\]
\[U_{day} = \text{mean wind speed at a 2-meter height (in m/s)}\]
\[P = \text{mean daily percentage of total annual daytime hours (Appendix 1)}\]
\[T = \text{mean daily temperature (in °C)}\]
\[ELEV = \text{mean height from sea level (in m)}\]
Thornthwaite—

Two other simple models referenced by John Parsons (1995) in his class notes at North Carolina State University are the Jensen-Haise radiation model and the Thornthwaite temperature based model. The Thornthwaite model is an empirical equation based only on temperature and is of the form

\[ PET = 1.6L_D \left( \frac{10 \cdot T}{I} \right)^a \left( \frac{10}{30} \right), \]  

(5)

where \( L_D \) = length of the day given as a ratio of the number of daylight hours divided by twelve hours (Appendix 2)

\( T \) = mean temperature for the day or month (in °C)

\( I \) = annual heat index

\( a \) = empirical constant

The annual heat index \( I \) is computed as

\[ I = \sum_{j=1}^{12} \left( \frac{T_j}{5} \right)^{1.514}, \]  

(6)

where \( T_j \) = long-term average monthly temperature of month \( j \).

The constant \( a \) is computed from \( I \) by either a linear or polynomial fit as

\[ a_1 = (0.016)I + 0.5 \]

or

\[ a_2 = (6.75 \times 10^{-7})I^3 - (7.71 \times 10^{-5})I^2 + (0.01792)I + 0.49239 \]  

(7)

The fraction \( (10/30) \) is a conversion factor to convert the units from [cm/month] to [mm/day].
The Jensen-Haise model is a more physically based equation and is computed as

\[ PET = C_t(T - T_x)R_s / 58.5, \]  

where \( T = \) daily mean temperature (in °C)

\( R_s = \) average daily incoming radiation (in ly/day). [See the Glossary for a definition of this unit.]

The constant 58.5 is a conversion factor to convert to [mm/day] and \( C_t \) and \( T_x \) are location-based constants computed as

\[ C_t = \frac{1}{C_1 + C_2 \cdot C_H}, \]

\[ C_1 = 38 - \left( \frac{2 \cdot ELEV}{305} \right), \]

\[ C_2 = 7.6, \]

\[ C_H = \frac{50}{e_2 - e_1}, \]

\[ T_x = -2.5 - 0.14(e_2 - e_1) - \frac{ELEV}{550}, \]

where \( e_2 = \) vapor pressure for mean maximum temperature for warmest month (in Pa)

\( e_1 = \) vapor pressure for mean minimum temperature for warmest month (in Pa).

In Norman, the warmest month (as indicated by data obtained from Oklahoma Climatological Survey) is July with a long term average minimum of 21.1°C and a similarly averaged maximum of 33°C. Using an average elevation of 339m and calculating vapor pressures from Equation (1), the Jensen-Haise equation for Norman becomes

\[ PET = 0.0203(T + 7.039)R_s. \]
Penman—

One of the first combination methods for potential evapotranspiration was developed by Penman. It has been modified many times from the original and the current general form given by Hatfield et al. (1996) is

\[
PET = \frac{\Delta}{\Delta + \gamma}(R_n - G) + \frac{\gamma}{\Delta + \gamma}E_a,
\]

where \( \Delta \) = slope of the saturation vapor pressure-temperature curve (in kPa/°C)

\( \gamma \) = psychometric constant (in kPa/°C)

\( R_n \) = net radiation (in mm/day water equivalent)

\( G \) = soil heat transfer (in mm/day water equivalent)

\( E_a \) = aerodynamic transport (in mm/day water equivalent).

The slope of the saturation vapor pressure-temperature curve can be calculated for temperatures greater than -23°C by

\[
\Delta = 3.38639[0.05904(0.007387 + 0.8072)^7 - 0.0000342].
\]

Parsons defines the psychometric constant as a measure of the balance between temperature gains and vapor pressure differences (1995) and calculates it as

\[
\gamma = \frac{c_p * p}{6.22 * \lambda},
\]

where \( c_p = 0.242 \) = specific heat of air at constant pressure (in cal/g°C)

\( p \) = atmospheric pressure (in kPa), calculated from Equation (2)

\( \lambda = 595 - 0.51^*T = \) latent heat of vaporization (in cal/g).

Net radiation is the incoming radiation minus the reflected radiation and the soil heat transfer represents the amount of heat lost through the soil. The Norman landfill site has a very thick hatch of dead vegetation; therefore, I neglected the soil heat transfer term in
my study. The aerodynamic transport term accounts for the ability of the wind to carry evaporated moisture away from the surface. The aerodynamic transport term can incorporate several different wind functions into the general form of

$$E_a = f(u)(e_s - e_d)$$  \hspace{1cm} (14)

where $e_s$ = saturation vapor pressure (in Pa), calculated by Equation (1)

$$e_d = e_s \cdot Rh = \text{saturation vapor pressure at the dewpoint temperature (in Pa)}$$

$u$ = wind speed at a height of 2 meters (in m/s).

Penman’s original wind function was denoted as

$$f(u) = 0.263(a + bu)$$ \hspace{1cm} (15)

The constants $a$ and $b$ are determined by the location and vegetation. Penman originally used 1 and 0.0062, respectively for $a$ and $b$, for grass in his studies. For additional values see Hatfield (1996). Many other forms have been given for the Penman wind function and some believe that each location requires a specially calibrated $f(u)$. However, in a discussion of Cuenca’s paper (1982), Hargreaves et al. (1983) noted that it is no longer necessary to calibrate the wind function empirically to a site. Instead a generalized wind function is adequate without calibration. Chow (1988) notes two functions in particular that work well, one by Doorenbos and Pruitt,

$$f(U) = 0.0027(1 + U / 100)$$ \hspace{1cm} (16)

and a modified form by Thom and Oliver,

$$f(U) = 0.0037(1 + U / 160)$$ \hspace{1cm} (17)

For both of the above equations $U$ is measured as the 24-hour wind run in [km/day] at a 2-meter height. The 24-hour wind run is the distance a particle would travel during the day given the prevailing wind conditions.
In this present work, I looked only at the simple wind functions, specifically Equations (16) and (17). There are, however, other more detailed formulations that could be tested.

For references to some of these formulations see Hatfield & Allen (1996), Cuenca & Nicholson (1982) and the discussion by Hargreaves et al. (1983).

**Priestley-Taylor—**

Priestley and Taylor proposed a simplification to Penman's equation for humid environments where advection may not play such a large role. As noted by Hatfield and Allen (1996), they arrived at the form

\[
PET = \frac{\Delta}{\Delta + \gamma} (R_n - G),
\]

where \( \alpha \) is a constant originally found to be 1.26 by Priestley and Taylor, but varying from 1.08 to 1.34 depending on vegetation and location. However, advection is thought to play a role in the value of \( \alpha \) and a correction has been developed by Jury & Tanner and noted by Hatfield & Allen (1996) as

\[
\alpha' = 1 + (\alpha - 1)(e_s - e_d)/(e_s - e_d),
\]

where \((e_s - e_d) = \text{mean vapor pressure deficit for the growing season.}\)

It was also noted that the values for \( \alpha \) and the vapor pressure deficit \((e_s - e_d)\) must be calibrated against a well-watered lysimeter. Since this was not available for my research, I have not used this correction factor.

Another correction for \( \alpha \) takes into account available soil water. Hatfield and Allen note it as

\[
\alpha' = \alpha[1 - \exp(-10.563ASW')],
\]
where $ASW = \text{available soil water at root depth.}$

They also noted that this does not cause a drastic reduction of PET until the available soil water is reduced by 50%. I used $ASW$ as a scaling factor for PET, and therefore, I did not implement this correction for $\alpha$ with the Priestley-Taylor model.

**Actual Evapotranspiration Equations:**

This section includes two different equations used to calculate actual ET and a brief description of each. Again all terms and symbols used in these equations are defined in the Glossary.

**Penman-Monteith Resistance Formulation—**

Models that incorporate resistance to evapotranspiration such as aerodynamic resistance to water vapor transfer and canopy resistance (or bulk stomatal resistance) are used to estimate actual ET. The aerodynamic resistance to water vapor transfer is just the resistance of the atmosphere to take on more moisture. The canopy, or bulk stomatal, resistance is the plants' resistance to losing moisture through their stomata. The Penman-Monteith model uses these resistance terms and has been suggested as a standard for ET calculation in several articles. Allen (1986) used the form described by Monteith as

$$ET = \frac{\Delta}{\Delta + \gamma^*} (R_n - G) + \frac{\gamma}{\Delta + \gamma^*} E_a,$$  \hspace{1cm} (21)

where $\Delta, \gamma, R_n,$ and $G$ are the same as for the Penman equation (Eq. 11) and

$$\gamma^* = \gamma (1 + r_c / r_{av}),$$  \hspace{1cm} (22)

where $r_c = \text{canopy (bulk stomatal) resistance (in s/m)}$

$r_{av} = \text{aerodynamic resistance to water vapor (in s/m)}$. 
The canopy resistance term is computed as

$$ r_c = \frac{500 - 0.857R_n}{LAI} , $$

(23)

where $R_n =$ net radiation (in cal/cm$^2$ day)

$LAI =$ leaf area index (in m$^2$/m$^2$), $LAI = 5h$

$h =$ mean canopy height (in mm).

Parsons defines leaf area index as the ratio of the area of the plant leaves to the soil surface area (1995). This formulation of $r_c$ allows for variable resistance responding to radiation. The vegetation responds to different levels of radiation by opening or closing stomata, thus altering the resistance to transpiration.

The aerodynamic resistance to water vapor can be computed as

$$ r_{aw} = \left[ \frac{\ln \left( \frac{z - d}{z_{om}} \right)}{\ln \left( \frac{z - d}{z_{0v}} \right)} \right] \left[ \frac{k u_z}{k^2 u_z} \right] , $$

(24)

where $k =$ von Karman constant of proportionality (0.41)

$u_z =$ wind speed at height $z$ (in m/s)

$z =$ wind and air temperature measurement height (in mm)

$d = 0.67h =$ displacement height where wind speed averages zero (in mm)

$z_{om} = 0.123h =$ surface roughness length for momentum transport (in mm)

$z_{0v} = 0.1 z_{om} =$ surface roughness length for vapor transport (in mm).

The aerodynamic transport term of the Penman-Monteith equation is defined as

$$ E_a = \frac{\rho c_p(e_s - e_d)}{\lambda \rho v_{av}} (8.64 \times 10^7) , $$

(25)
where \( \rho = \) density of air (in g/cm\(^3\))

\( c_p = \) specific heat of air (0.24cal/g°K)

\((e_s - e_d) = \) vapor pressure deficit (in mb)

\( \lambda = 595 \times 0.51 T = \) latent heat of vaporization (in cal/g)

\( \gamma = \) psychometric constant (in mb/°K)

\( p = \) atmospheric pressure (in mb), calculated by Equation (2)

\( r_{av} \) is calculated by Equation (24).

The density of air is assumed constant for each day and can be calculated by

\[
\rho = \frac{0.0003484(p + 0.622e_d)}{T(1 + e_d p^{-1})},
\]

where \( T = \) mean daily air temperature (in °K)

\( e_d = \) vapor pressure at dewpoint temperature (in mb), calculated by Equation (1).

**Advection-Aridity—**

Another form used to calculate actual ET was proposed by Brutsaert and Stricker (1979) and is termed the advection-aridity approach. The equation is a combination of Penman's equation with the first part of Bouchet's argument, which considered symmetry between potential and actual ET, and is computed as

\[
ET = (2\alpha - 1) \frac{\Delta}{\Delta + \gamma} (R_n - G) - \frac{\gamma}{\Delta + \gamma} E_a
\]

where all of these terms are as above in the Penman combination method and \( \alpha \) is in the range of 1.26 to 1.28. More information about Bouchet's argument can be found in Brutsaert (1982). Upon closer examination, the above equation can be simplified to two
equations that have already been mentioned: the Penman combination and the Priestley-Taylor. In fact, this form of the advection-aridity equation is just twice the Priestley-Taylor equation (Eq. 18) minus the Penman equation (Eq. 11).

All of the above methods calculate either potential or actual evapotranspiration in [mm/day]. Most methods available in the literature calculate PET, since less knowledge is needed about plant and surface characteristics for these methods. I have selected a variety of forms for my study.

**Methods:**

Since all of my work used existing forms of data and did not involve lab or field experimentation, a materials section is not included. All computations for the models were done in Excel spreadsheets. For May and June of 1997 the models are compared with pan evaporation data; such data were not available for the remaining ten months of the year.

**Criteria:**

To evaluate properly the accuracy of the models, it was necessary to develop some criteria. For my purposes, I decided that all evaluations should be based upon comparisons between models and pan evaporation measurements. The models were evaluated as follows:

1. Conduct a sensitivity test on the parameters for each model.

2. When various forms are available for a model, compare these to decide if all forms are necessary. Choose the highest predictor (to get a conservative estimate) for comparison with other models.
3. Graph all models together in a general comparison to gain more insight. Capture general trends and notice any deviations.

4. Graph temperature, radiation and relative humidity and compare to trends in model output. Look particularly at spikes in the model data and compare with the meteorological data.

5. Compare each model with the pan evaporation data from Chickasha. Note those which do not correspond at all. Also note deviations in general trends. View temperature comparison for Norman and Chickasha and see if these explain deviations.

6. Compare each model with the Penman-Monteith model. Since this model has been recommended as a standard, the models that follow this most accurately will be considered for use in the infiltration model.

To begin modeling with each equation, I first organized the meteorological data from the Mesonet files. These data are transferred in 30-minute increments from the original data to a spreadsheet at the end of each month and then stored to disk. The increments had to be summed and averaged over each day to prepare the data for use in the equations.

Tables of other necessary parameters are provided in the Appendices. Briefly, these are:

1. Daily percentage of annual daylight hours, $P$, for the Blaney-Criddle method (Appendix 1)
2. Predicted pan coefficients for scaling Chickasha data (Appendix 1)
3. Length of each day for the entire year as computed by a Fortran program, for the Thornthwaite method (Appendix 2)

The pan evaporation data from Chickasha were scaled according to the coefficient table in Appendix 1. This was based upon average monthly wind and relative humidity, rather than on daily values, which could introduce some error. The windward side distance, or fetch, is the distance from the evaporation pan to vegetation. I am unsure of this
measurement at the Chickasha site. To keep the scaling factors similar for both months, I used the values from the coefficient table in Appendix 1 listed for 10m in May and 100m for June.
Results:

During the two calibration months, May and June, each model was within the same order of magnitude with the scaled pan evaporation data. However, the pan evaporation data for the first few days of June did not compare well with the various model estimates. In an effort to alleviate the daily spikes and smooth the data, the pan evaporation comparisons for May and June were made on a weekly basis, rather than a daily.

There was one major disappointment in my research, and it was related to the advection-aridity model. With certain conditions present this model predicts negative evapotranspiration. Looking at Equation (27) and setting $\alpha$ equal to 1.28, it was easy to determine that it would produce negative results if

$$R_s < \frac{\gamma^* E_a}{1.56 \Delta}$$  \hspace{1cm} (28)

The original study done by Brutsaert and Stricker only considered June through September when testing the model. In my study, the model seemed to predict accurately from February to August. From September through January, the results were increasingly negative and did not make sense. However, because the model did have some value from February through August, I decided to leave the results in my study with the concession that I would not recommend this model for prediction in the months from September through January.

In the remainder of this section, I present calibration results for May and June and general results of all models for the entire year. To estimate actual ET, all model estimates for
PET were scaled by the ratio of available soil moisture to maximum available soil moisture. The daily available soil moisture was taken to be the average of the half-hourly soil moisture measurements taken by the Mesonet station each day. Previous calibration of the Mesonet soil moisture probes determined the maximum available soil moisture. I chose to use measurements from two probes at the west cell and one at the east cell to scale the PET. In all subsequent graphs I indicate these three locations by west-c, west-s, and east-s where c indicates that the probe is located in the clay portion of the landfill cap and s indicates that the probe is located in topsoil. The pan evaporation measurements were scaled by 0.74 in May and 0.71 in June.

**Individual Methods – Pan Evaporation Comparison & Sensitivity:**

**Thornthwaite:**

The Thornthwaite method as presented by Parsons (1995) included two methods for calculating the exponential factor. The value of $a$ was tested for sensitivity by comparing the ET results given for each of the two methods of calculating $a$ (Eq. 7).

In this paper I refer to the linear method as $a_1$ and the polynomial method as $a_2$. The formulation proved to be insensitive to this parameter (in fact the results were nearly the same). However, the model using $a_2$ resulted in a slightly higher PET estimate and will be used in all subsequent calculations.

The Thornthwaite method was within the same magnitude as the pan evaporation data for both May and June. However, the resulting ET underestimated the pan evaporation data for both months. Figure 1 shows the comparison of the Thornthwaite estimate for each cell with the pan ET estimates for May and June.
The Thornthwaite method follows general trends somewhat during May, but very little in June. The model estimates are about 15 to 30 [mm/week] less than the pan evaporation data for both months. This could be very significant in the long run, with model estimates accounting for only 55\% of the pan measurements.

A closer examination of the temperature profile for Chickasha and Norman reveals some differences in daily trends. Figure 2 compares the temperatures for both May and June in Norman and Chickasha. While the temperature profiles are comparable for the month of May, they deviate for most of June. The closeness in agreement for May could explain why the general trends are followed more closely. In June the temperature differences could be a source of deviation between the pan and model ET. (The temperature data from Chickasha in Figure 2 are computed averages of the recorded daily highs and lows. For more information about the recorded Pan data and my processing techniques, please see Appendix 3.)
Figure 2. Daily temperature comparison for Norman and Chickasha

This figure shows a nearly exact agreement through May followed by rather poor agreement in June. It might be the case that Chickasha is warmer than Norman during the summer months, however, without year-round temperature data from Chickasha it is difficult to draw any conclusions.

Jensen-Haise:

Sensitivity tests were conducted on elevation for this method. The elevation at the Norman landfill site varies from 336m to 341m above sea level. An average elevation of 339m was used in this and other methods that require elevation. Upon varying the elevation and recalculating the PET, no significant difference was noted. The greatest deviation was on the order of six-thousandths mm/day. This is insignificant and was not considered as an error in the calculations. Therefore, all subsequent calculations use the average elevation of 339m for all locations.

This makes physical sense over the small range of elevations. The atmospheric pressure,
boiling point and other physical characteristics are indirectly related to the elevation. Over a large range of heights, this might cause noticeable deviations in ET. However, with the small range considered here, this variable makes little difference.

For both May and June the magnitude of the model estimates are comparable with the pan measurements. Figure 3 shows the estimates for May and June.

![Figure 3. Weekly comparison of Jensen-Haise with pan ET for May & June](image)

For both months the model underpredicts what was actually measured. In May the weekly Jensen-Haise calculations fit the scaled pan evaporation data well. The June estimates are not as good an indication of the measured pan data, but do follow the rising and falling trends until the fourth week. This deviation may be attributed to the slight temperature differences in June, but radiation differences would result in more deviation.

The Jensen model is based upon radiation levels, which were not available for the Chickasha area. Had these been available it would have been interesting to look at radiation differences between Norman and Chickasha.
Blaney-Criddle:

Sensitivity tests were run on elevation for this method as well. Again, due to the small range of elevations, this model was insensitive to elevation.

The Blaney-Criddle method compares fairly well with the pan evaporation data. Figure 4 shows weekly comparisons for May and June. The model's estimate of ET follows the general trends of the pan evaporation data very well until the last two weeks of June. This again could be due to the differences in radiation and temperature at the two sites. However, in magnitude this model fits the pan data very well.

Figure 4. Weekly comparisons of Blaney-Criddle with pan ET for May & June

Priestley-Taylor:

The parameter $\alpha$ in this method can vary from 1.08 to 1.34 depending upon the vegetation. Two corrections have been suggested for this value. The first, noted in the literature review, accounts for vegetation by calibrating $\alpha$ with a well-watered reference lysimeter. This was not possible for our study. The second correction accounts for
available soil moisture at root depth. However, this correction only changes $\alpha$ by about 0.001. Therefore, I did not use either of the $\alpha$ corrections suggested by the literature.

The Jensen-Haise and Priestley-Taylor methods are both radiation-based and have comparable estimates of PET. Therefore, the Jensen-Haise method was used as a basis for comparison to determine an adequate value for $\alpha$. I allowed $\alpha$ to vary from the original value of 1.26 suggested by Priestley and Taylor, to the maximum value of 1.34.

To get a more quantitative idea of how much the Priestley-Taylor PET deviated from the Jensen-Haise method with each $\alpha$, I looked at the average differences in calculated ET. These differences are presented in Table 4.

<table>
<thead>
<tr>
<th>Avg. ET difference</th>
<th>alpha = 1.26</th>
<th>alpha = 1.28</th>
<th>alpha = 1.30</th>
<th>alpha = 1.34</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6702</td>
<td>0.6358</td>
<td>0.5960</td>
<td>0.5601</td>
<td></td>
</tr>
</tbody>
</table>

As $\alpha$ became larger, the difference in PET became smaller. I chose the largest value of $\alpha$ as it had the smallest average difference. For all subsequent uses of this model I will let $\alpha$ take the value of 1.34.

The Priestley-Taylor method for calculating PET is comparable to the pan evaporation, however, it does underestimate the pan measurements slightly. The general trends appear to follow the evaporation data. As shown in Figure 5, this model exhibits the same weekly patterns. However, the last week of June predicts a decrease while the
measurements show an increase.

![Graph showing ET comparison](image)

**Figure 5.** Weekly comparisons of Priestley-Taylor with pan ET for May & June

**Penman Combination:**

I was able to compare two different wind functions for the Penman model. One is currently being used in the larger infiltration model and was formulated by Doorenbos and Pruitt and the other is a similar formulation by Thom and Oliver (see Equations 16 and 17). Most likely due to the similarity of the formulations, the PET's calculated by both of these wind functions were nearly identical.

No other sensitivity tests were necessary as each variable was calculated directly from climatological data. Due to a thick hatch at the site (see Glossary), which inhibits direct evaporation from the surface, the equation has been simplified to include only net radiation without the soil heat transfer term.

Analysis of the Penman model with each of the wind functions shows that the Thom...
wind function produces slightly higher estimations of PET. The difference, however, was not significant and I chose to use the Doorenbos-Pruitt formulation for future uses of the Penman equation, since it is currently being used in the infiltration model.

The Penman model, shown in Figure 6, compares very well with the pan evaporation data for May. However, June does not follow the trends of the pan data as well.

![Figure 6. Weekly comparisons of Penman with pan ET for May & June](image)

**Figure 6.** Weekly comparisons of Penman with pan ET for May & June

**Advection-Aridity for actual ET:**

The advection-aridity method uses the same simple formulation for the wind function that the Penman combination uses. The only major difference is that units and constants are converted to reflect pressures in millimeters of mercury. So the resulting wind function becomes

\[ f(u) = 0.35(1 + 0.54u) . \]
The advection-aridity model was found by 
Brutsaert and Stricker (1979) to be valid for values of $\alpha$ between 1.26 and 1.28. After a series of sensitivity tests it was determined that the larger value produced the best results. (Since this model predicts actual ET, it was unnecessary to scale it by soil moisture. Therefore, there is only one estimate rather than one for each soil moisture probe as for the PET models.) As shown in Figure 7, this method fit the daily pan evaporation data fairly well for both months, with a couple of exceptions. Between the second and third weeks of May the pan estimate is dropping while the model estimate predicts a rise in ET. Also between the third and fourth weeks of June, the pan estimate is rising while the model estimate is falling. Overall, however, this method compares well with the pan evaporation data.

Figure 7. Weekly comparisons of Advection-aridity with pan ET for May & June

Penman-Monteith:

I used two different estimates from this model, one for each of the two cells at the landfill. This was based upon a difference in mean crop canopy height, not soil moisture.
Since the average crop heights were very similar, the results did not differ greatly for the two cells; however, to be as accurate as possible, both estimates were used.

This method compared fairly well with the pan evaporation estimates. Weekly estimates fit well for May, but the third-week estimate deviates from the trend of the measurements. In June the trends were followed, but the slopes were not comparable to the pan evaporation, as shown by Figure 8. Otherwise, the model estimates follow the general trends of the pan evaporation data.

![Figure 8](image-url)  
*Figure 8. Weekly comparison of Penman-Monteith with pan ET for all cells*
Comparison of all Methods:

All methods were within the same order of magnitude for their predictions of ET. In this section I compare all models collectively over the course of a year and capture general trends. In order to provide a consistent reference point, and since no actual measurements were made at the landfill, each model will also be compared with the Penman-Monteith, which has been recommended as a standard for ET estimates (Allen et al. 1995). Graphs of meteorological and terrestrial conditions are also provided for reference.

The general trend of evapotranspiration estimates over the entire year resembles a bell-shaped curve. As shown in Figure 9, there is a major deviation from this trend for several of the models in July of 1997.

![ET estimates for clay at the west cell in 1997](image)

**Figure 9.** ET estimates for clay at the west cell in 1997

This dip is only exhibited by the scaled potential models and a closer examination of the soil moisture profile in Figure 10 reveals a drastic decrease in moisture from the
surrounding months. This brings up an important difference in the behavior of the two types of models. While the potential ET models must be scaled down by soil moisture, the actual ET models are not limited by this physical characteristic at the site. This is a major downfall of the actual ET models and more research should be done to include this variable in the models.

![Soil moisture profiles](image)

**Figure 10.** Soil-moisture profiles for both cells in 1997

The soil moisture depends heavily upon precipitation for replenishment. Figure 11 shows that there was very little rainfall in July to provide this moisture. Although this is also evident in January, March, and December, the lower temperatures in these months allow the ground to retain its moisture.
Figure 11. Precipitation profile at the landfill for 1997

Figure 9 also shows a noticeable deviation by the Penman combination and Advection-aridity models in November. At this time, there is no clear explanation for the behavior of the Penman combination model. The deviation of the Advection-aridity model illustrates the main problem associated with it. Due to the nature of the equation, when certain conditions exist (see Equation 28), the model predicts overwhelmingly negative results. This prohibits the use of this model during the winter months and minimizes its effective range.

The overall bell shape of the ET estimates is mimicked in the temperature and radiation profiles for the landfill in 1997. Figures 12 and 13 show these profiles. Each model was based, in part, on either one or both of these variables and there is most likely a correlation between the noted behaviors.
The profiles for wind speed and relative humidity exhibit a more constant pattern. Figures 14 and 15 show little deviation in the monthly averages for these variables from month to month. With these mostly constant profiles it is difficult to determine the importance of these variables for the model estimates.
From Figure 14, it is evident that the wind speed is slightly higher during the spring months. This could be a factor in the earlier peak of ET estimates for the combination models than the other models. (Notice that the Blaney-Criddle and Penman models in Figure 9 peak around April and May rather than July.)
Before I compare each model with the Penman-Monteith, I should justify why I am using this model as a standard. Allen (1986) concluded in his study that the Penman-Monteith provided the most accurate estimates with the most consistency over a variety of sites. He also noted that the use of this model might preclude the need for calibrating the wind function to location. In my study, the ability to vary the surface roughness variables in the model as plant activity changed at the site produced estimates that more closely fit our expectations. The cap of each cell is covered with a thick hatch of dead plants and the root systems of living plants. This inhibits moisture from escaping easily, especially when there is no plant activity to draw the moisture out. Because of this, we expected very little evapotranspiration to occur during the winter months. As Figure 16 shows, the Penman-Monteith model predicts near zero ET for the months of November through February. This is consistent with the range found in Allen’s study.

![Figure 16. ET estimates for soil at the west cell in 1997](image)

In the next few sections I will be trying to get a quantitative idea of how much each model differs from the Penman-Monteith in its predictions. I used the sum of the absolute
value of the monthly difference over the entire year as a measure of the goodness of fit for each model with the Penman-Monteith. All numbers reported in the following sections were computed in this way. Comparisons for each of the landfill cells were similar; therefore, I have only presented graphs for the east cell in the following sections.

**Penman-Monteith and Radiation Models:**

The Jensen-Haise and Priestley-Taylor radiation methods resulted in almost identical results. This is most likely due to the calibration of the Priestley-Taylor alpha parameter by comparison to the Jensen-Haise model. However, they did not follow the trends of the Monteith at all times. Figure 17 shows these three models for 1997.

![Figure 17. Comparison of radiation models with the Penman-Monteith](image)

The radiation models tend to underestimate ET in the summer and overestimate at all other times. This could be due to various conditions which are present at the site and not accounted for by the models, the most likely of these being the advective power of the wind. Because these simplified models do not account for more of the conditions present at the site, they may not predict ET as accurately. However, if a site does not have the
ability to measure many meteorological and terrestrial conditions, these models are not bad. The differences from the Penman-Monteith ET predictions for the radiation models are summarized in Table 5.

Table 5. Yearly deviation between Penman-Monteith and radiation models

<table>
<thead>
<tr>
<th></th>
<th>west-c [mm/year]</th>
<th>west-s [mm/year]</th>
<th>east-s [mm/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jensen-H.</td>
<td>428</td>
<td>424</td>
<td>438</td>
</tr>
<tr>
<td>Priestley-T.</td>
<td>427</td>
<td>425</td>
<td>437</td>
</tr>
</tbody>
</table>

**Penman-Monteith and Temperature Model:**

The Thornthwaite temperature-based model predicts the lowest ET of all the models. Although it is a very simplified approach, it still requires historical data from the site, which may make the model unfeasible for many situations. In my study, I found that calculating ET on a monthly basis using monthly averages of temperature and soil moisture resulted in lower monthly estimates of ET when compared with a daily approach. Figure 18 compares the estimates given by the daily and monthly approach with the Monteith.

![Figure 18. Comparison of temperature model with the Penman-Monteith](image)
In both cases the Thornthwaite model underestimated ET in the summer and was the closest to the Monteith during the remainder of the year. However, the magnitude of deviation in the summer months produced a large deviation from the Monteith. The differences from the Penman-Monteith ET predictions for the temperature models are summarized in Table 6.

Table 6. Yearly deviation between Penman-Monteith and temperature models

<table>
<thead>
<tr>
<th>Thorn-daily</th>
<th>Thorn-monthly</th>
</tr>
</thead>
<tbody>
<tr>
<td>west-c [mm/year]</td>
<td>west-s [mm/year]</td>
</tr>
<tr>
<td>368</td>
<td>370</td>
</tr>
<tr>
<td>370</td>
<td>379</td>
</tr>
</tbody>
</table>

Penman-Monteith and Combination Models:

The Blaney-Criddle model is hard to classify as one particular type of model, because it uses wind speed and sunshine data (not radiation), I have placed it in the combination category. It is somewhat different from the Penman combination in that it does not follow the general trends exactly. However, on an order of magnitude scale, it fits well in this category. Figure 19 compares these two combination models with the Monteith.

Figure 19. Comparison of combination models with the Penman-Monteith
Again, these models tend to underestimate during the summer months and grossly overestimate during the rest of the year. This large deviation could be caused by the soil moisture ratio, which scales the potential ET to get an estimate of actual ET. The differences from the Penman-Monteith ET predictions for the combination models are summarized in Table 7.

<table>
<thead>
<tr>
<th></th>
<th>west-c [mm/year]</th>
<th>west-s [mm/year]</th>
<th>east-s [mm/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blaney-C.</td>
<td>530</td>
<td>562</td>
<td>475</td>
</tr>
<tr>
<td>Penman Comb.</td>
<td>671</td>
<td>668</td>
<td>643</td>
</tr>
</tbody>
</table>

**Penman-Monteith and the Advection-Aridity Model:**

Although the advection model uses a combination approach, because it estimates actual ET without being scaled I have considered it separately. It seems to follow the general bell-shaped nature that the Monteith does, but the tendency to predict negative results in all months other than the summer limits its usage, unless the original algorithm is modified. During its effective period it compares very well with the Monteith. However, as shown in Figure 20, from September till December it appears to oscillate about zero.
Since the Advection-aridity model estimates actual ET and is not scaled by the soil-moisture, it compares very well with the Monteith. The differences from the Penman-Monteith ET predictions were 388 [mm/year] for the west cell and 389 [mm/year] for the east cell. Limiting the comparison to only the summer months results in total summer differences of 149 [mm] for each of the cells.
Conclusions:

Table 8 summarizes the total evapotranspiration predicted for 1997 by each of the models and the sum of their monthly deviations from the Penman-Monteith over all twelve months. The first row in each soil category is the total yearly ET predicted by the model and the second row is the deviation from the Penman-Monteith model.

<table>
<thead>
<tr>
<th></th>
<th>Jensen-H.</th>
<th>Priestley-T.</th>
<th>Thornth-d</th>
<th>Thornth-m</th>
<th>Blaney-C.</th>
<th>Penman</th>
<th>Advection</th>
<th>Monteith</th>
</tr>
</thead>
<tbody>
<tr>
<td>west soil</td>
<td>649.5</td>
<td>618.4</td>
<td>420.4</td>
<td>374.6</td>
<td>838.6</td>
<td>937.7</td>
<td>750.8</td>
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<td>423.9</td>
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<td>379.1</td>
<td>561.5</td>
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<td>388.0</td>
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</tr>
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<td>635.9</td>
<td>437.3</td>
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<td>750.8</td>
<td>647.7</td>
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<td>368.4</td>
<td>370.0</td>
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<td>671.2</td>
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<td>0.0</td>
</tr>
<tr>
<td>east soil</td>
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<td>606.3</td>
<td>422.3</td>
<td>384.5</td>
<td>804.4</td>
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<td>642.6</td>
<td>389.1</td>
<td>0.0</td>
</tr>
</tbody>
</table>

From this table, it appears that none of the models compare really well with the recommended Penman-Monteith. Surprisingly, the original Penman drastically overestimates ET when compared with the modified Penman-Monteith and has the greatest deviation in yearly ET estimates. Overall the advection model does not do too badly, but again problems with negative results prohibit its usage on a yearly basis. The Blaney-Criddle and Penman combination models have the highest deviation from the Monteith on a yearly basis and I would not recommend their usage. The Jensen-Haise and Priestley-Taylor radiation models have the second highest deviation, but are closest in total predicted ET for 1997. The Thornthwaite temperature model deviates from the Penman-Monteith nearly the same amount that it predicts and I would not recommend its usage either.
It appears that there is no simplified model that compares really well with the Penman-Monteith, which could be due to errors in the models themselves, an over-simplified method for scaling the PET equations or some other problem. By graphing the PET models before they are scaled in Figure 21, I noticed that most of the PET models follow the general trend of the Penman-Monteith very well. (Since they have not yet been scaled, they have considerably higher results.)

![Figure 21. Unscaled PET models compared to the Penman-Monteith](image)

This indicates to me that the cause of the poor agreement is most likely related to the scaling factor and the Penman-Monteith equation itself. If the PET models are going to be scaled down by the ratio of actual to maximum soil moisture at root depth, then the Penman-Monteith model should be adjusted to include this parameter. Obviously, the limiting effect of available moisture in the soil plays a large role in the amount of possible evapotranspiration. (I.e., it is not possible to evaporate more moisture than is available in the soil.)
Therefore, by observing the unscaled PET and considering only the total predicted ET for each PET model, I would have to say that either of the Jensen-Haise or Priestley-Taylor radiation models would give good approximations on a yearly basis. Note that they would not be as accurate for smaller time periods, but they would give satisfactory yearly totals.

The intention of this study was to quantify the ET at the landfill and to compare various models with the widely recommended Penman-Monteith for inclusion in the larger infiltration model. Without actual measurements from the Norman, OK landfill site it is difficult to say any one model is better than the rest. Having said that, I must conclude that none of the models I have studied would be adequate substitutes for the Penman-Monteith (outside of use within the infiltration model). This is not to say that one of the other models might not fit well with data from the actual site, but only that they do not compare well with the suggested standard. Although I cannot conclude what the actual ET activity at the site is, the results of the modeling study indicates that an order of magnitude estimate for total yearly ET is around 650 [mm/year] (using the predictions from the Penman-Monteith model).

A topic of future research would be to collect actual ET data from the site by some form of direct measurement and compare these measurements to model predictions. It would also be instructive to calibrate the ET models by using soil moisture measurements, in conjunction with results from the infiltration modeling, as an indication of ET at the site.
Appendix 1. Various tables used in calculations

Table 9. Daily percentage of Annual Daylight Hours (P) for Northern Hemisphere

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<thead>
<tr>
<th>Latitude (degree)</th>
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<th>FEB</th>
<th>MAR</th>
<th>APR</th>
<th>MAY</th>
<th>JUNE</th>
<th>JULY</th>
<th>AUG</th>
<th>SEPT</th>
<th>OCT</th>
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<th>DEC</th>
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<td>0.274</td>
<td>0.274</td>
<td>0.274</td>
<td>0.274</td>
<td>0.274</td>
<td>0.274</td>
<td>0.274</td>
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<td>0.280</td>
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<td>0.287</td>
<td>0.285</td>
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<td>0.264</td>
<td>0.261</td>
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<td>0.355</td>
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<td>0.211</td>
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</table>

**Table from Allen and Pruitt (1986)**

Table 10. Pan coefficients for class A pan

<table>
<thead>
<tr>
<th>Wind, in Km / day</th>
<th>Windward side dist of green crop in meters</th>
<th>Average relative humidity= &lt;40%</th>
<th>Average relative humidity= 40-70%</th>
<th>Average relative humidity= &gt;70%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light &lt;175</td>
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<td>0.60</td>
<td>0.70</td>
<td>0.77</td>
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<tr>
<td></td>
<td>10</td>
<td>0.61</td>
<td>0.71</td>
<td>0.78</td>
</tr>
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<td></td>
<td>100</td>
<td>0.71</td>
<td>0.80</td>
<td>0.87</td>
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<tr>
<td></td>
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<td>Moderate 175-425</td>
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<td>0.77</td>
<td>0.80</td>
</tr>
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<td>Strong 425-700</td>
<td>1</td>
<td>0.48</td>
<td>0.57</td>
<td>0.63</td>
</tr>
<tr>
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<td>0.49</td>
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<td>Very Strong &gt;700</td>
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<td>0.57</td>
<td>0.63</td>
<td>0.64</td>
</tr>
</tbody>
</table>

**Table from Frevert (1983)**

The boxed values for both tables indicate those used in my research. There was no "science" involved in choosing pan coefficients. I used the average monthly wind speed and relative humidity for each month to determine the area of the chart I should use. Nothing was known about the windward side distance at the Chickasha location, so I chose pan coefficients that were close to each other.
Appendix 2. Thornthwaite day length calculator

The following Fortran program was provided in John Parsons’ class notes for the calculation of the Thornthwaite length of day (1995). It computes the length of day as the ratio of daylight hours to twelve hours when given an input of latitude. (I.e., 12 hours gives $L_d = 1$)

```
C******************************************************
C thmday.f - daylength program, 2/18/92
C INPUTS:
C Latitude of location degrees and minutes—ddmm
C OUTPUTS:
C Table of Thornthwaite’s Ld by day
C DISCLAIMER:
C You are free to use and distribute this
C program, however the authors assume no
C liability for the use or misuse of the program.
C******************************************************
Implicit double precision (a-h, o-z)
Dimension rel (366)
write(*,*)'Enter latitude (ddmm)'
read(*,*)lat
i= lat/100
j = lat - i*100
xlat1 = dfloat(i)
xlat2 = dfloat(j)
rlat = 0.0174533*xlat1 + 0.0002909*xlat2
sinlat = dsin(rlat)
coslats = dcos(rlat)
do 10 nd=l,366
xnd = nd
xm = 0.0172264*(-0.6+xnd)
xlam = 4.874239 + xm + 0.0334762*dsin(xm)
+ 0.0003502*dsin(xm+xm)
yd = 0.397900*dsin(xlam)
xd = dsqrt(ll-yd*yd)
d=datan2(yd,xd)
xd = (-0.0414544-(sinlat*dsin(d)))/(coslat*dcos(d))
yd = dsqrt(l-xd*xd)
rel(nd) = 0.0111111*datan2(yd,xd)*57.29578
10 continue
write(*,19)
write(*,20) xlat1, xlat2
do 15 jj-1,366,10
if (jj.gt.360) then
jend=366
else
jend=jj+9
endif
write(*,22) jj-1, (rel(jjj), jjj=jj jend)
continue
stop
format(/,l Ox,’Thornthwaite Daylight Hour Calculator’)
format(/,’ ’, ’Latitude = ’, f4.0, ’, f4.0, ’, degrees ’, f4.0, ’, minutes’,/)
2x ’------ daylight hours Ld (fraction of 12) ------’; /,’ Day’,
’ 1 2 3 4 5 6 7 8 9 10 ’)
format(i5,10(f6.2))
end
```
### Table 11. Output from Thornthwaite Daylight Hour Calculator

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<th>Day</th>
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<th>4</th>
<th>5</th>
<th>6</th>
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Appendix 3. Pan evaporation measurements

Table 12 shows the raw pan measurement data as they were obtained from Chickasha, Oklahoma. The average daily temperature was computed by taking the arithmetic average of the daily high and low temperatures. The daily evaporation was calculated by taking the difference of the previous day and that day and adding any precipitation reported for that day.

Table 12. June 1997 pan evaporation for Chickasha, Oklahoma

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Glossary:

Abbreviations:
ET—evapotranspiration
PET—potential or reference evapotranspiration
FAO—United Nations Food and Agricultural Organization
Mesonet—network of meteorological measurement stations across Oklahoma

Selected Definitions:
Advection—horizontal movements of atmospheric conditions, particularly water vapor. Thus, the advective power of the wind is its ability to take moisture away from the surface and into the atmosphere.
Cell—a mound of garbage that has been filled until it reaches a certain height and is then capped with clay and covered with topsoil and vegetation when another cell is created. Thus, only one cell should be active at a time. The Norman landfill had three cells, each of which was dug into the water table with no protective lining placed at the bottom.
Enclosure—a tent-like enclosure placed around an area of vegetation and various measuring devices. Measurements of the water added to the system and the moisture in the air are taken at predetermined times. Since the tent separates the system from the outside conditions, the measured moisture in the air is an estimation of ET for the system. This is not exactly the same as ET for the unrestricted environment, but does serve as an estimate.
Evapotranspiration—the combined process of plant transpiration and direct evaporation from the soil.
Hatch—thick covering of dead plant materials and root systems on the surface of each cell at the landfill (about 2-3in).
Langley [Ly]—English unit for radiated energy per unit area with an equivalence of 697.32 Ly/min = 1 W/m².
Lysimeter—a pan equipped with holes in the bottom in which a portion of the soil with vegetation is placed. The pan is placed back in the hole (created by removing the soil) with a means of measuring the water escaping through the bottom of the pan. This provides a measure of ET by taking the difference of water added to the system and the water exiting through the holes.
Pan Evaporation—method that is used to estimate regional open water evaporation. This can be scaled appropriately to estimate ET. Measurements of the water level in the pan are taken daily and records of all water added or removed manually are kept. The daily evaporation is then calculated by taking the difference in measurements for successive days and factoring in the precipitation, refilling, etc.

Equation Notation:
$\alpha$—constant associated with the Priestley-Taylor equation, ranges from 1.26-1.34
$\Delta$—slope of the saturation vapor pressure curve at given temperature
$\gamma$—psychrometric constant (Balance between temp. gain and vapor pressure differences)
$\lambda$—latent heat of vaporization
$\rho$—density of air
Equation Notation: (cont)
ASW—available soil water at root depth
ELEV—mean elevation from sea level
LAI—leaf area index

$E_a$—aerodynamic transport term
$E_r$—radiation term, equals $R_n - G$
$G$—soil heat transfer term
$I$—annual heat index calculated from average monthly temperatures
$L_D$—length of the day as fraction of sunshine hours to twelve hours
$N_{ratio}$—ratio of actual to possible sunshine hours in a 24-hour period
$P$—mean daily percentage of total annual daytime hours
$R_h$—relative humidity
$R_n$—net radiation (incoming minus reflected radiation)
$R_s$—average daily incoming radiation (in Ly/day) or (W/m²)
$T$—mean Temperature for a given time period, often in °C
$U$ or $u$—mean daily wind speed, (or daily wind run)

c$_p$—specific heat of water at constant pressure
d—zero plane displacement (height within vegetation where average wind speed is zero)
e$_a$—saturation vapor pressure calculated from mean temperature
e$_d$—vapor pressure at dew-point temperature or $R_h * e_a$
f(u)—wind function used in the aerodynamic transport term
$h_c$—mean height of vegetation (or canopy height)
p—atmospheric pressure
r$_{av}$—aerodynamic resistance to water vapor
r$_c$—canopy resistance (or bulk stomatal resistance)
z—height of wind speed measurements (2m)
z$_{om}$—surface roughness for momentum transfer
z$_{ov}$—surface roughness for vapor transfer

Figure Legend Notation:
A-A—Advection-aridity combination ET model
B-C—Blaney-Criddle combination PET model
J-H—Jensen-Haise radiation PET model
Pcomb—Penman combination PET model
P-M—Penman-Monteith combination ET model
P-T—Priestley-Taylor radiation PET model
Thorn-d—Thornthwaite temperature PET model (daily method)
Thorn-m—Thornthwaite temperature PET model (monthly method)
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